A STUDY OF PERMANENT ELECTRON BEAM RADIATION EFFECTS ON THIN FILM SINGLE JUNCTION QUANTUM INTERFEROMETER DEVICES

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THESIS

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ON THIN FILM SINGLE JUNCTION QUANTUM
INTERFEROMETER DEVICES

by

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Thesis Advisor: J. R. Neighbours

June 1972

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on Thin Film Single Junction Quantum
Interferometer Devices

by

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
June 1972

ABSTRACT

Mercereau-Nisenoff, single junction, superconducting, quantum interferometer devices were irradiated at room temperature with 60 Mev electrons.

After irradiation these devices showed no optically observable gross physical defects. There were, however four levels of electrical response to radiation damage dependent on the total accumulated dose as follows:

1. device would superconduct and the detected radio frequency signal amplitude remained essentially unchanged at a dose level of $\sim 10^5$ Rads,

2. device would superconduct but the detected radio frequency signal amplitude changed markedly at a dose level of $\sim 10^7$ Rads,

3. device would superconduct, but no detected radio frequency signal was observable also at a dose level of $\sim 10^7$ Rads,

4. device would no longer superconduct at a dose level of $\sim 10^8$ Rads.

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ACKNOWLEDGEMENTS

The author wishes to extend particular appreciation to the following individuals for their time and assistance in conducting this study:

Professor John R. Neighbours, my thesis advisor.

Professor John N. Dyer for his advice and the use of the NPS Linear Accelerator.

Dr. William S. Goree and Mr. Victor Hesterman of DeVelco Corp. for providing the SQUID devices and their testing before and after irradiation.

My wife, Jane, and our children for their patience and encouragement.

I. INTRODUCTION

Magnetic and electric measurements of unprecedented sensitivity may now be made using superconducting quantum electronic systems. Table I lists some of these measurements and the sensitivities possible. These measurements are based on the properties of a weakly superconducting device in which both London's [1] concept of fluxoid quantization and the Josephson effect [2,3] combine to produce a highly sensitive and periodic response to magnetic flux. The flux sensing element is called a SQUID (Superconducting QUantum Interference Device), or is sometimes referred to as a superconducting, "weak link". A brief examination of Table I makes obvious the utility of these devices in all branches of science and engineering.

In view of the possible future application of these devices in the field of military hardware and space exploration, the purpose of this study was to determine the permanent effects of high level steady state radiation environments on these devices. The radiation used was that obtained from 60 Mev electrons at the Naval Postgraduate School Linear Accelerator.

TABLE I

SQUID MEASUREMENT SENSITIVITY

Quantity Measured	Sensitivity Possible for 1 sec Averaging Time
Magnetic Field	10^{-11} Gauss
Magnetic Flux	10^{-11} Gauss-cm^2
Magnetic Field Gradient	10^{-12} Gauss/cm
Magnetic Suseptibility	10^{-13} cgs
Noise Temperature	10 μK°
DC Voltage	10^{-13} Volts
AC Resistance	10^{-10} ohms
AC Mutual Inductance	10^{-11} henries

II. THEORY OF OPERATION OF SQUID DEVICES

The particular SQUID used in this study was of the Mercereau-Nissenoff type, an enlarged diagram of which is shown as Fig. 1 and a picture as Fig. 2.

These superconducting devices are composed of a proprietary alloy which is vacuum evaporated on the cylindrical substrate. The thickness of the film using this technique can be controlled to within a tolerance of $\pm$ 100A°, which in turn is the tolerance on the thickness of the bridge. The width of the bridge (approximately one half micron) is determined by mechanically scribing the film under a microscope. As is self evident this procedure allows for considerable variance between samples in the cross-sectional area of the bridge. The success rate in manufacturing these particular type SQUID device using this procedure varies between 20 to 50 percent for those that are of good enough quality to be used in instruments. Consequently they are expensive and only a limited number could be made available for this study.

The way the SQUID operates, very qualitatively, is that if an axial magnetic field is applied a superconducting circulating current is induced in the film. All the current must flow through the bridge and at some value it will reach the value of critical current for the bridge given by

$$i_c = \frac{\phi_o}{2\pi L}$$

where ϕ_o is the basic flux quantum and is given in terms of fundamental constants by

$$\phi_o = h/2e = 2.07 \times 10^{-7} \text{ gauss}$$

h is Plancks constant, e is the electronic charge, and L is the self inductance of the device. When this critical value of current is reached the bridge attempts to become normally conducting, however the time scale is such that before this can be accomplished the magnetic flux inside the cylinder changes allowing the current through the bridge to decrease and the bridge remains superconducting. The detailed process of the way magnetic flux enters the cylinder from first principles is complex and in fact there is no complete theory for it. However, the total flux linking the cylinder must remain quantized [5].

If a coil is wound around but not in contact with the device and a radio frequency field is applied such that the amplitude of the R.F. is sufficient to induce several flux quantum units change at the device, then it can be shown that the EMF induced across the coil is given by; [6]

$$\mathrm{EMF} \approx \phi_{RF}\,\omega\,J_1\left(2\pi\frac{\phi_{RF}}{\phi_o}\right)\mathrm{Cos}\left(2\pi\frac{\phi_{dc}}{\phi_o}\right)\mathrm{Sin}\;\omega t$$

where ϕ_{dc} is the ambient DC field at the device. It can be seen that the EMF induced in the coil is proportional to the first order Bessel function J_1 of the R.F. flux and to the cosine of the d.c. flux.

In typical systems using SQUID devices the mean square noise flux, or power spectrum, referred to the flux quantum ϕ_o is white noise from audio frequency down to essentially zero frequency, and of magnitude approximately $10^{-8}\ \mathrm{Hz}^{-1}$; therefore, the noise flux of the basic sensor is approximately $10^{-4}\ \phi_o/\sqrt{\mathrm{Hz}}$ of the post detection bandwidth. It is the smallest of this noise flux combined with the intrinsic smallness of the flux quantum (ϕ_o) which leads to the unusual sensitivity of instruments using SQUID sensors [5].

These devices are generally used in electronics systems using a circuit such as that shown in Fig. 3. This particular circuit (Fig. 3) is used when it is desired to utilize the unique properties of the SQUID as a magnemometer, and was the circuit used to test the SQUIDS before and after irradiation in this study.

The operational characteristic of this circuit are such that if the average flux in the SQUID is modulated at an audio rate and at a peak to peak amplitude of about $\phi_o/2$ while the detected output voltage is amplified, synchronously detected at the audio frequency, integrated and fed back to the sensor input, then the system will "lock on". The voltage at the output of the integrator will then be linearly proportional to flux changes at the input to the SQUID. In this way the periodic response to flux is effectively linearized and the dynamic response of the system is increased. The overall system is referred to as a "flux locked loop". Mechanically it is analagous to a linear servo loop.

Figures 4 and 5 are the idealized outputs of the above circuit at the RF detector output jack shown in Fig. 3. Figure 4 is a plot of the amplified and detected R.F. output as a function of the amplitude of the R.F. excitation. The characteristic step pattern demonstrates the quantization of magnetic flux. The position of the steps on the diagram depends periodically on the average flux coupled into the SQUID. The two traces A and B demonstrate the two extremes of this periodic response. Figure 5 is a plot of the detected R.F. output as a function of the average flux coupled into the SQUID, referred to in the literature as ϕ_{dc}. The response of the device under the simultaneous application of an R.F. bias field and a dc or low frequency field is to act

as a parametric up converter. Figure 5 is the result of the general phenomenon of hetrodyne detection. Since one input signal, ϕ_{dc} contains only low frequency Fourier terms, the heterodyne terms lie close to the R.F. frequency and the total signal (carrier plus sidebands) appears at the diode detector as an amplitude modulated wave and is detected as such. The decreasing amplitude of this detected output with increasing R.F. excitation is a result of the first order Bessel function response. The triangular peaks and valleys correspond to flux values produced by the extremun of traces A and B in Fig. 4 and are of period ϕ_o, which results from the periodic dependence of the steps in Fig. 4 on the average flux (ϕ_{dc}) coupled into the SQUID. The lower trace in Fig. 5 is the "signal" looked for using the circuit discussed above, and was the signal studied during this investigation.

MERCEREAU-NISENOFF SQUID

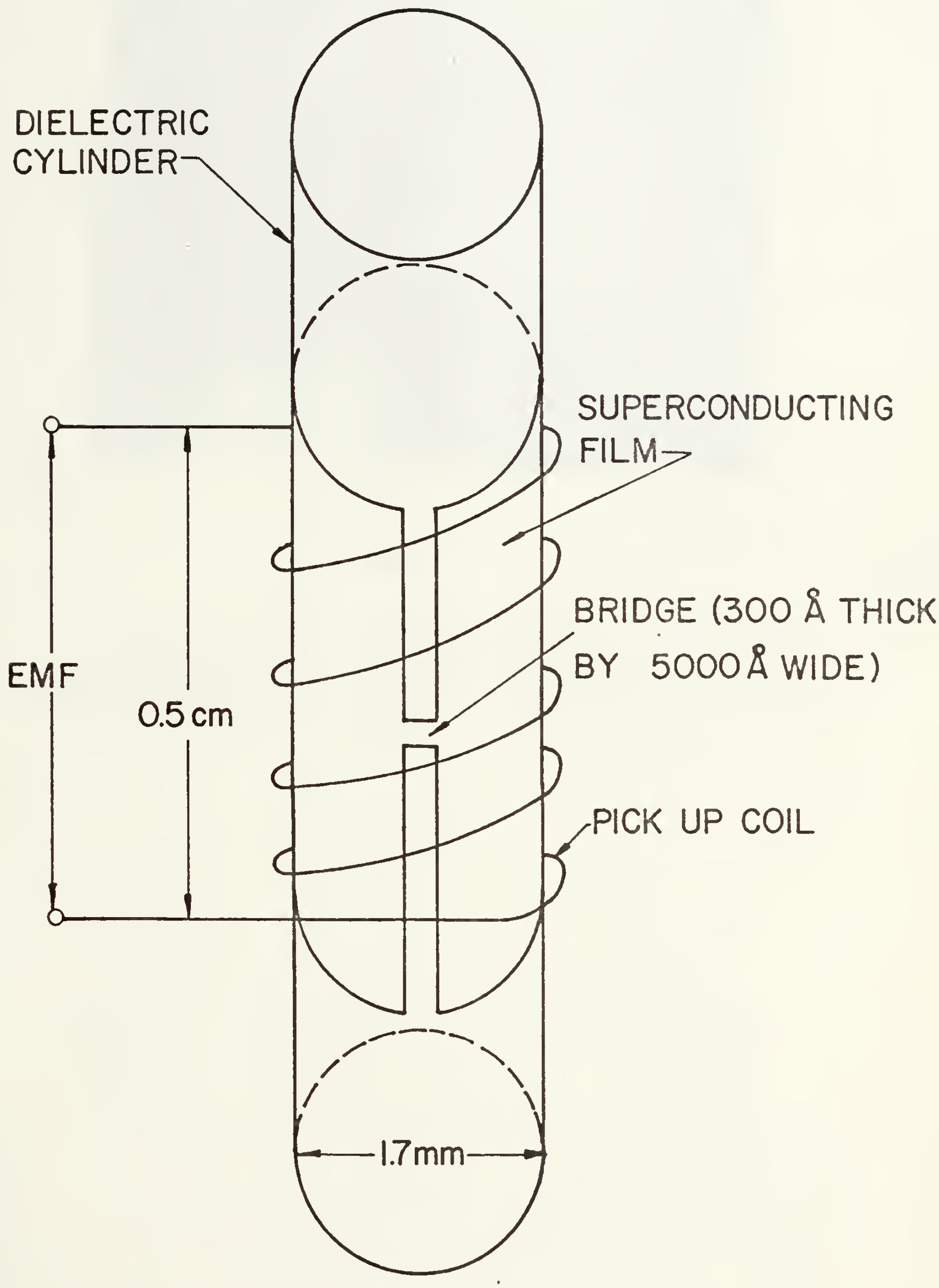


FIGURE 1

Figure 2

Sample 40A after irradiation, dose 1×10^9 Rads. The white specks are dust particles reflecting the illuminating light and not defects in the film due to radiation.

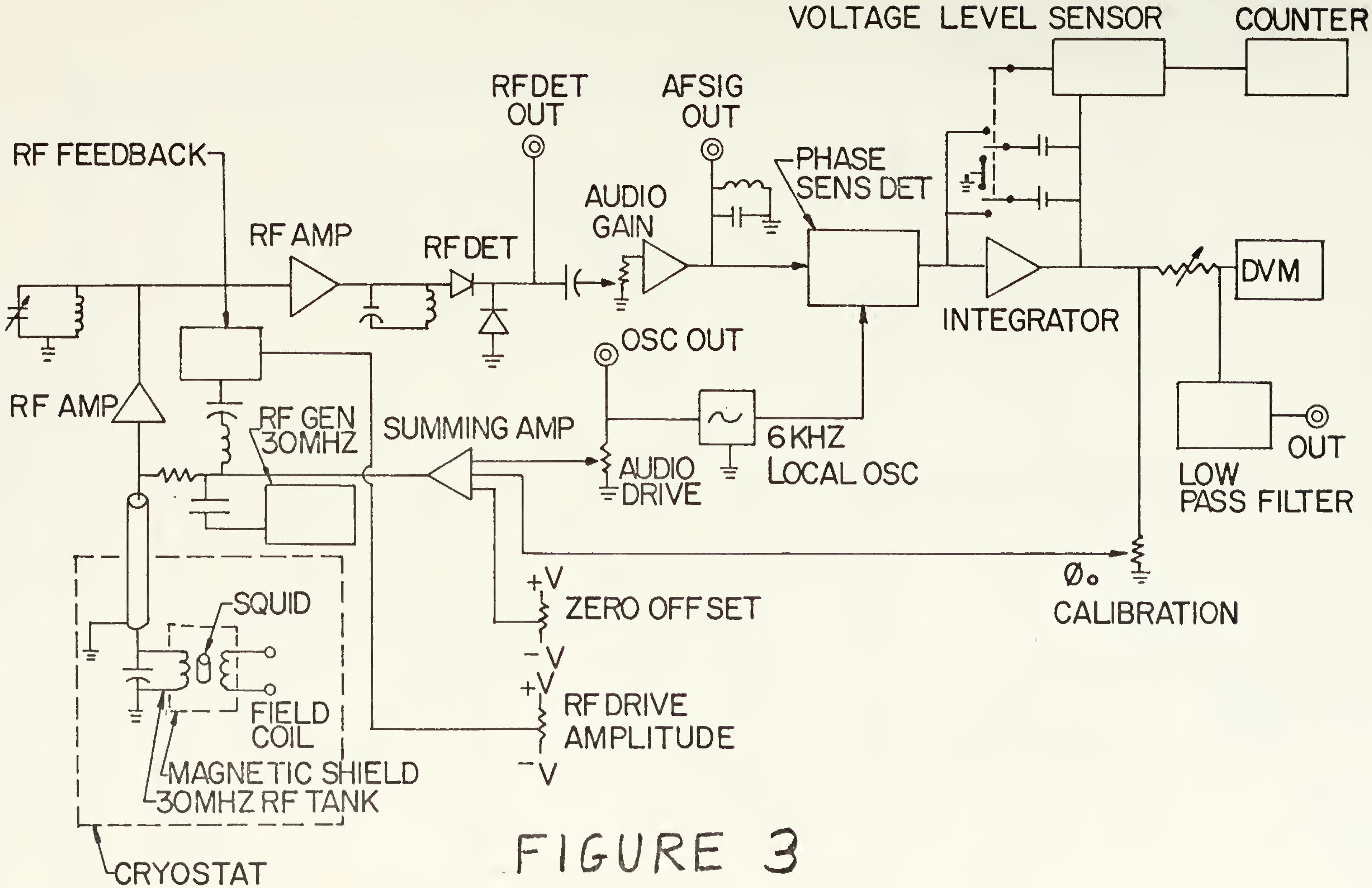

VOLTAGE LEVEL SENSOR
COUNTER
RF DET OUT
AFSIG OUT
RF FEEDBACK
PHASE SENS DET
AUDIO GAIN
RF AMP
RF DET
INTEGRATOR
DVM
OSC OUT
RF AMP
RF GEN 30MHZ
SUMMING AMP
6 KHZ LOCAL OSC
AUDIO DRIVE
OUT
LOW PASS FILTER
Ø₀ CALIBRATION
+V
ZERO OFF SET
-V
SQUID
+V
RF DRIVE AMPLITUDE
-V
FIELD COIL
MAGNETIC SHIELD
30MHZ RF TANK
CRYOSTAT

FIGURE 3

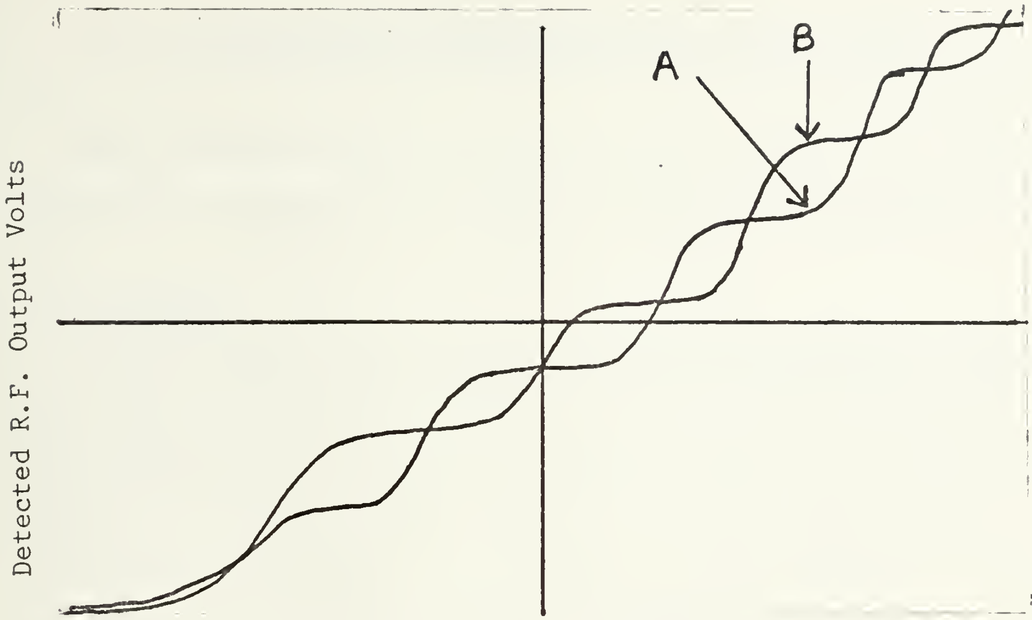


Figure 4

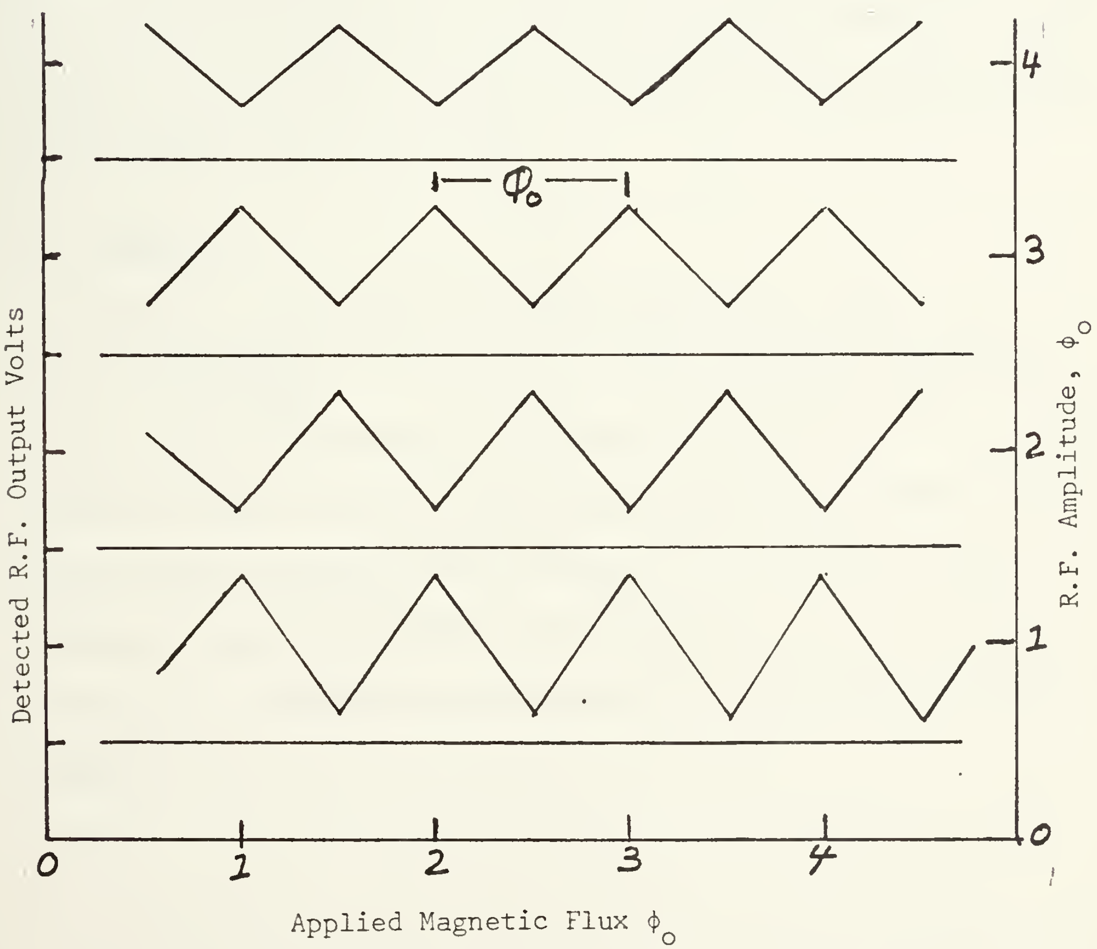


Figure 5

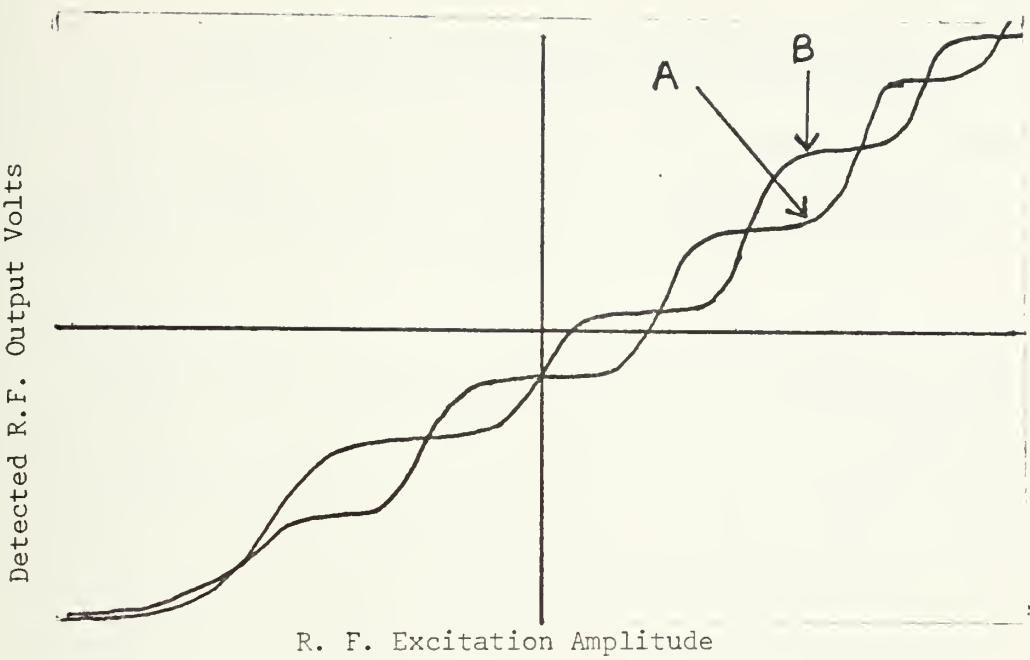


Figure 4

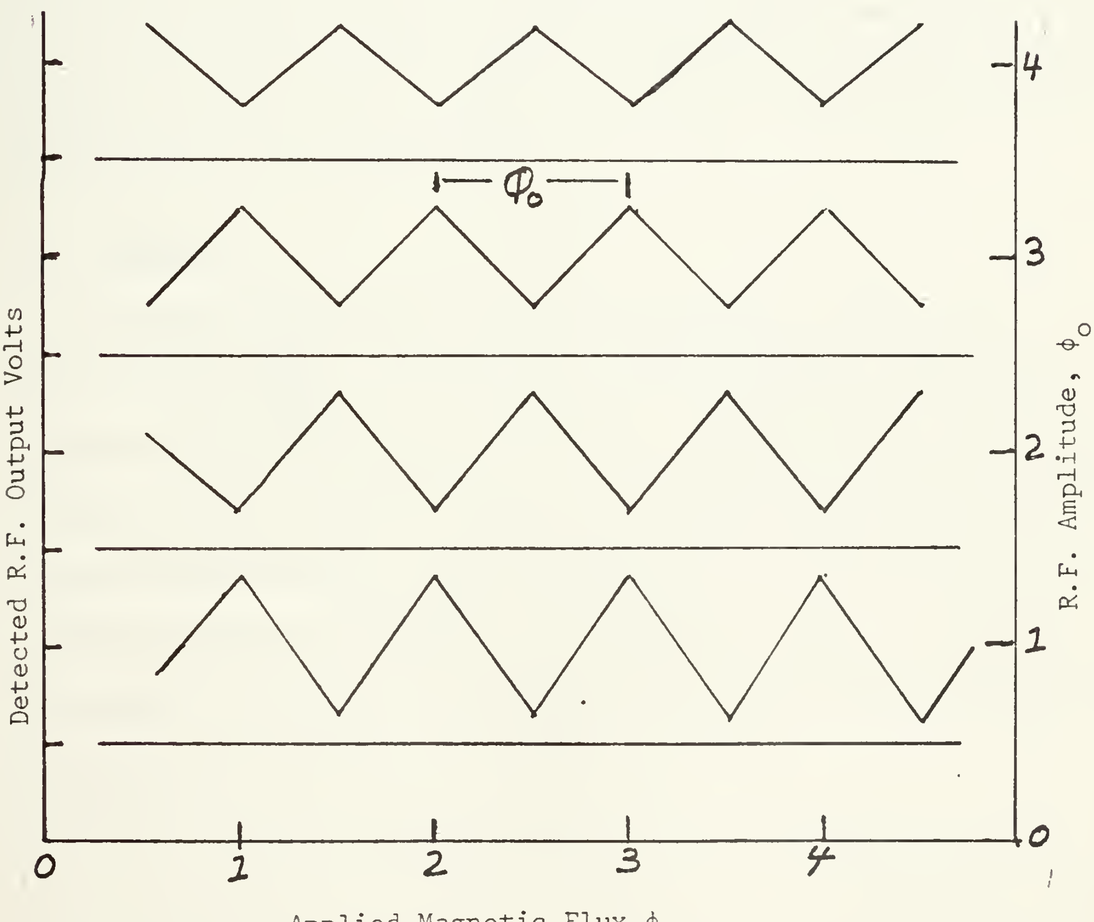


Figure 5

III. ELECTRON BEAM INTERACTIONS IN TIN AND INDIUM

High energy electrons (60 Mev for this study) from a linear accelerator interact with matter by ionization and radiation [9].

A. RADIATION

Incident high energy electrons produce Bremstrahlung radiation when they interact with target nuclei. For 60 Mev electrons interacting with the propriatary film nuclei, the energy loss due to this radiation is comparable to the ionization loss; however, the photons produced in this manner have mean free paths for absorption much greater than the thickness of the film (300A°). Therefore, nearly all of the photons produced in this manner escape from the film. The energy loss due to this mechanism is neglected when calculating the total absorbed dose of the film.

B. IONIZATION

The energy loss due to ionization expressed in units of Mev-cm^2/gm $\left[\frac{1}{\rho}\frac{dE}{dx}\right]$ as a function of incident energy is essentially constant for all materials for incident electron energies greater than 30 Mev [10]. For the proprietary alloy used in depositing the film on these devices 60 Mev electrons lose 1.514 Mev-cm^2/gm while passing through the film [10]. This energy loss was the only one considered in the total dose and dose rate calculations for this study [Appendix A].

IV. EXPERIMENTAL PROCEDURE

The SQUID devices used in this study were supplied by and tested before and after irradiation by the Develco Corporation with the author assisting. The circuit discussed in section II was used. Oscilloscope photographs and measurements of the signal (lower trace in Fig. 5) and the circuit parameters necessary to produce it were taken before bringing the devices to the Naval Postgraduate School for irradiation. The devices were examined optically and photographs taken before placing them in the accelerator. The devices were then placed in the accelerator and irradiated to a predetermined level using the dosimetry discussed in Appendix A. After removal from the accelerator it was found that all of the devices were radioactive usually at a level of approximately 80 MR/HR. However this radioactivity was short lived and fell to a level of approximately 1 MR/HR in 24 hours.

After the radioactivity had fallen to a level at which the devices could be handled, they were re-examined optically and photographs retaken to determine if there had been any gross physical damage to the film or the device. They were then returned to the Develco Corporation where they were retested using the same circuit. Oscilloscope photographs and measurements of the signal and the circuit parameters after irradiation were then retaken.

Optical examination of the first two samples 65C and 40A[1] showed that the bridge area of the film could not be observed, due to its dimensions, with sufficient resolution to determine if any defects had

[1] Sample numbers are those assigned by the Develco Corporation.

been radiation induced in this critical area. Two of the next group of samples (76D and 71C) were therefore coated with a very thin (several angstroms) film of evaporated gold and examined under an electron microscope.

Since only 12 samples were made available for this study several samples were irradiated twice at different total accumulated dose levels to extract the maximum amount of information before the device failed. Two samples were irradiated to a level of $\sim 10^5$ Rads. Four samples were irradiated to a level of $\sim 10^7$ Rads. Two samples were irradiated to a level of $\sim 10^8$ Rads. Four samples were irradiated to a level of $\sim 10^9$ Rads. The effect on these devices of the above dosages is tabulated in section V, Table II.

V. RESULTS

A. ELECTRICAL

The electrical results of this study are tabulated in Tables II and III and displayed as Figs. 6, 7, 8, and 9.

Table II lists the gross electrical effects with increasing total accumulated dose. In this table all the devices were superconducting and had approximately the same detected R.F. signal amplitude (about 5 MV) before irradiation. The reason for the multiple entries is that due to the limited number of samples available some of the samples were irradiated twice. For instance, samples 76E and 71C were originally irradiated to a dose of $\sim 10^5$ rads and after irradiation it was found that they were both superconducting and the amplitude of their signal was essentially unchanged. They were therefore put through the whole process again at a dose level several orders of magnitude higher in order to extract the maximum amount of information possible before the device failed.

Table III lists the circuit parameters necessary to obtain the oscilloscope trace of the detected signal (shown in Figs. 6, 7, 8, and 9) for those samples which still had a detectable signal after irradiation. The scale for Figs. 6, 7, 8, and 9 was vertical deflection 10 Mv/cm; horizontal deflection 50 μsec/cm.

Examination of this data revealed several levels of permanent electrical effects which were a function of the total accumulated dose. These levels were as follows:

a) Device would superconduct and a signal whose amplitude was essentially unchanged as compared to before irradiation was still detectable. Samples 76E and 71C in

Table II at a dose level of ~ 10^5 Rads and Figs. 6 and 7 illustrate this effect. However comparison of the data in Table III for these two samples at the same level of irradiation shows little correlation between the two in the effect on the circuit parameters. For instance, sample 76E both the R.F. drive and the dc level increased after irradiation whereas for 71C the R.F. drive increased and the dc level decreased.

b) Device would superconduct and a signal was detectable; however, in this case there is a marked change in its amplitude and the circuit parameters necessary to produce it. Sample 76D at a dose level of ~ 10^7 Rads illustrates this effect. Examination of Table III and Fig. 9 shows that the signal amplitude increased by a factor of eight and there was a marked change in three of the five circuit parameters. It is further worthy of note that sample 86B at the same dose level had very little change in its signal amplitude and not nearly as large a change in its circuit parameters.

c) Device would superconduct but there was no longer any detectable signal. Samples 76E and 71C in Table II showed this effect after their second exposure for a total accumulate dose of ~ 10^7 Rads.

d) Device would not superconduct rendering it completely inoperative. This effect was always observed for a total accumulated dose of ~ 10^8 Rads or greater, with one exception, sample 65C after its first exposure at this level. An explanation of this exception is given later. Examination of Table II shows that samples 40A and 96C showed this effect after their first and only exposure and samples 86B and 76D after their first exposure at this level; however, they had been irradiated once before at a level lower by a factor of ten.

B. PHYSICAL

Optical examination of the devices after irradiation showed no observable gross physical damage to the superconducting film or to the device as a whole. The electron microscope examination of samples 76D and 71C was inconclusive as the bridge area of the film could not be located after the deposition of the thin gold film. It was thought that this film would increase the resolving power of the electron microscope, but apparently it had the opposite effect.

From Table II it can be seen that there was one exception to the devices failing completely at a dose of 10^8 Rads or greater. This was sample 65C after its first exposure. Sample 65C was the first sample irradiated. The film on these devices are only 300Å thick deposited on a thin walled dielectric substrate,and because of this and their overall dimensions they are somewhat fragile and difficult to handle as the film must not be scratched or touched. A holder was therefore designed in which to place the device to protect it while it was being irradiated. The cover of the holder had to be transparent in order to be able to determine when the device was properly centered in the electron beam. The author made an unfortunate choice of material for the cover of this first sample, a clear thin piece of Lucite plastic acrylic (a long chain polymer). Subsequently a thin walled glass tubing was used. The result of this choice of material is shown in Fig. 10. The beam melted a hole through the cover and deposited a great deal of cloudy plastic on the device. One possible explanation as to why 65C did not fail completely is that in melting its way through the plastic the beam lost a considerable amount of its energy and many of the electrons were scattered far enough out of the beam by their interaction with the cover and the plastic deposited on the film, so that the dose absorbed by the film was different by several orders of magnitude from that calculated.

TABLE II

DOSE AND DOSE RATE VS EFFECT AFTER IRRADIATION

Sample #	Total Accumulated Dose (Rads)	Maximum Avg Dose Rate (Rads/sec)	Superconducting	Signal
76E	6.04×10^5	2.08×10^4	yes	yes
71C	6.04×10^5	2.08×10^4	yes	yes
86B	6.04×10^7	5.5×10^5	yes	yes
76D	6.04×10^7	5.5×10^5	yes	yes
76E	6.04×10^7	5.5×10^5	yes	no
71C	6.04×10^7	5.5×10^5	yes	no
86B	6.0×10^8	7.3×10^5	no	no
76D	6.0×10^8	7.0×10^5	no	no
40A	1.27×10^9	6.5×10^5	no	no
65C	1.27×10^9	6.8×10^5	yes	no
65C	2.50×10^9	6.1×10^5	no	no
96C	2.57×10^9	1.2×10^6	no	no

TABLE III

SIGNAL RESPONSE CIRCUIT PARAMETERS

Sample #	Dose Rads	R.F. Drive Freq (MHz)	R.F. Drive MV (RMS)	DC Level Volts	AF Signal MV P-P	Noise MV P-P
76E	0	32.6	.30	1.8	5	4
76E	6×10^5	32.9	2.1	5.35	5	5
71C(GP)	0	32.5	4.3	2.8	5	5
71C(GP)	6×10^5	32.9	2.5	5.8	3.5	2.0
76D(GP)	0	32.6	4.7	1.65	5	4
76D(GP)	6×10^7	32.7	.21	.22	40.3	3.0
86B	0	32.4	2.7	5.6	5	5
86B	6×10^7	32.8	1.49	4.9	6	5

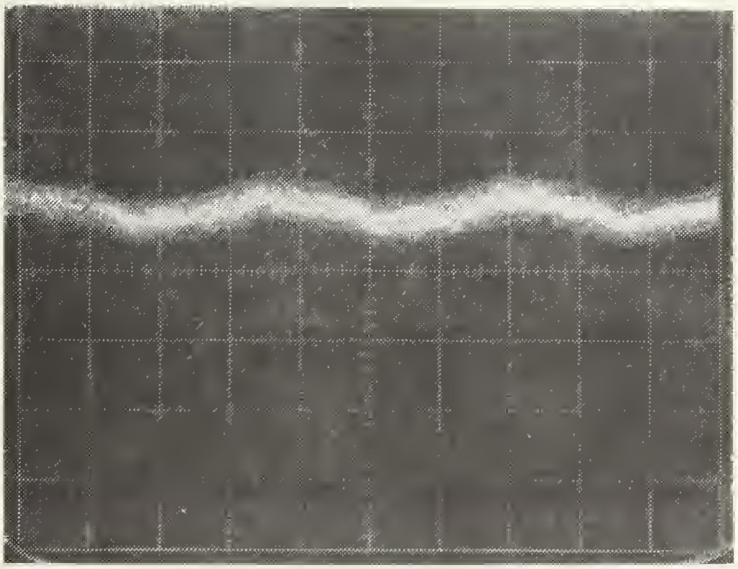
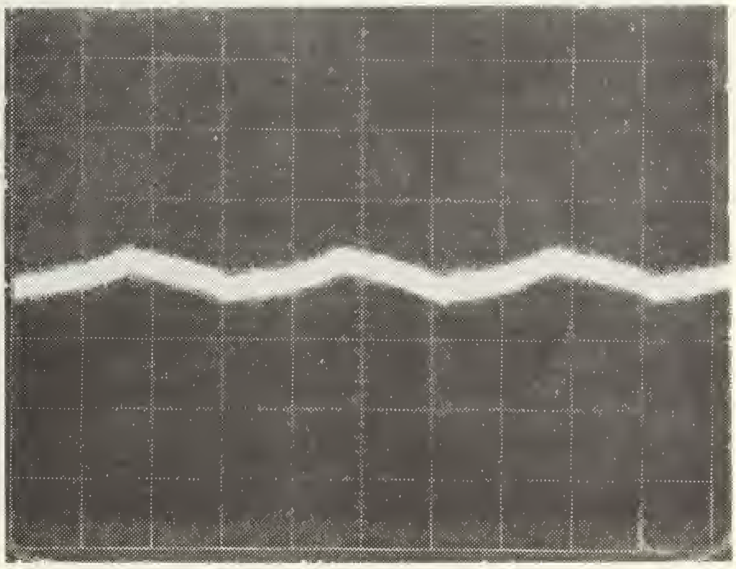


Figure 6

Sample 76E before (above) and after Irradiation (below). Dose 6 x 10^5 Rads.



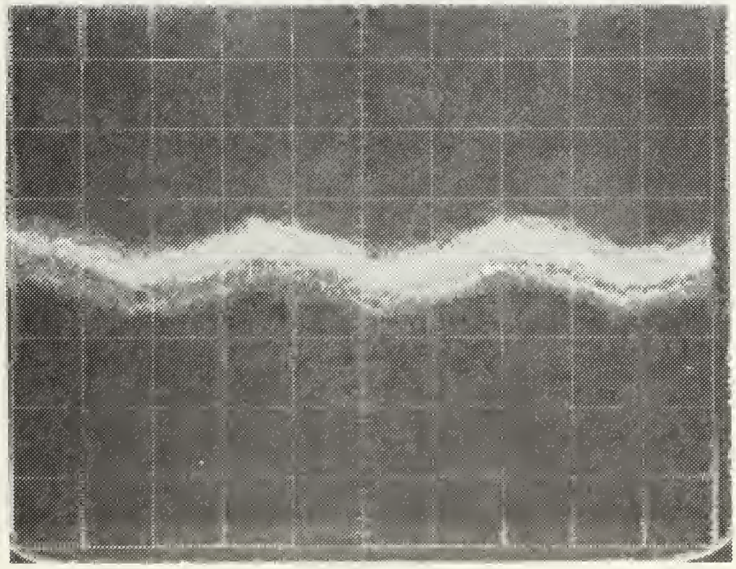
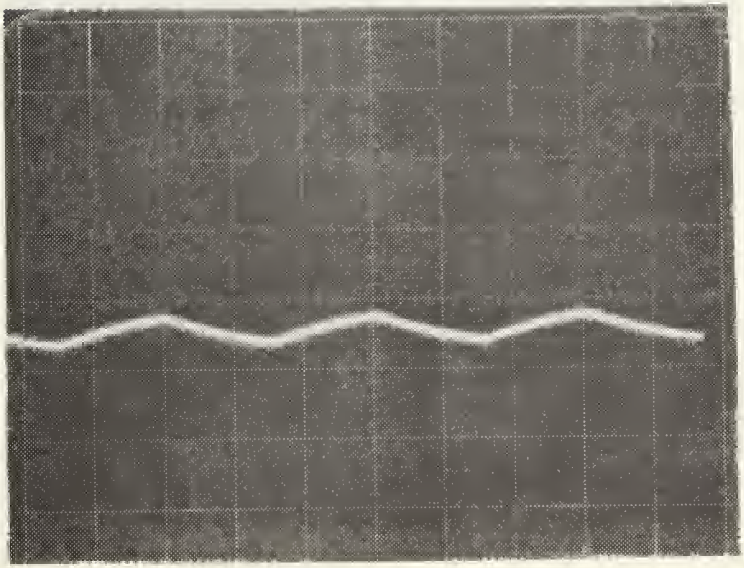


Figure 7

Sample 71C Before (above) and After (below) Irradiation. Dose 6×10^5 Rads.



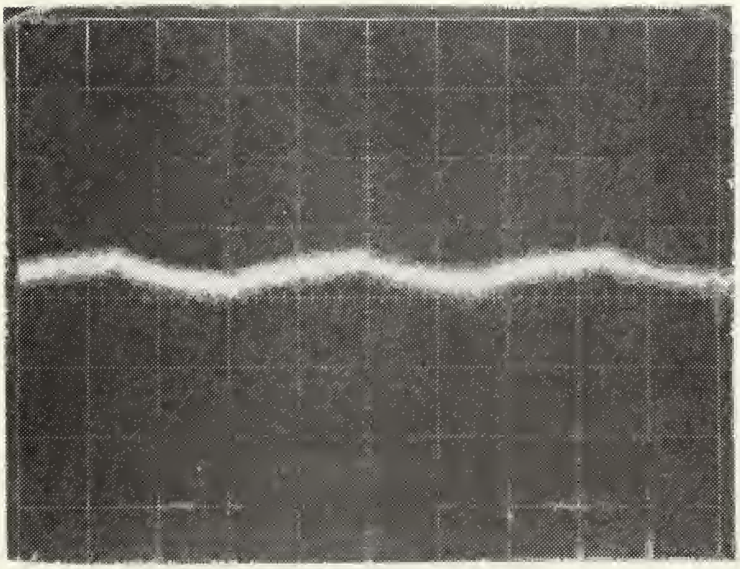
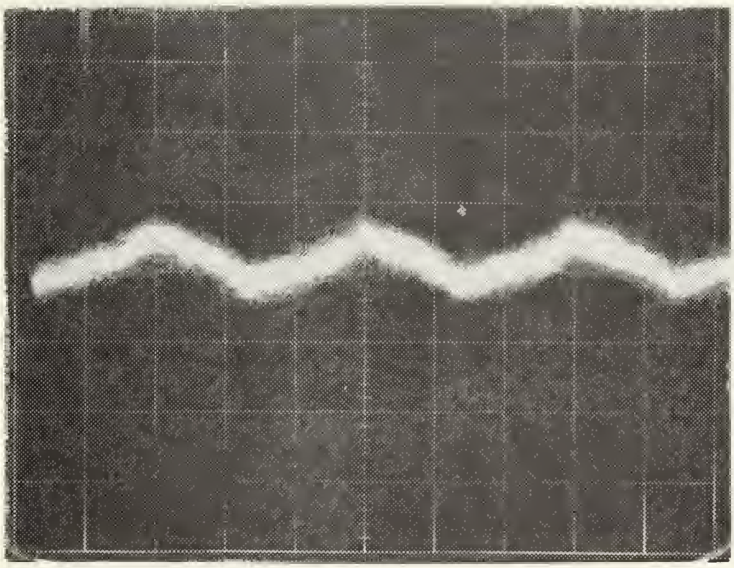


Figure 8

Sample 86B Before (above) and After (below) Irradiation. Dose 6×10^7 Rads.



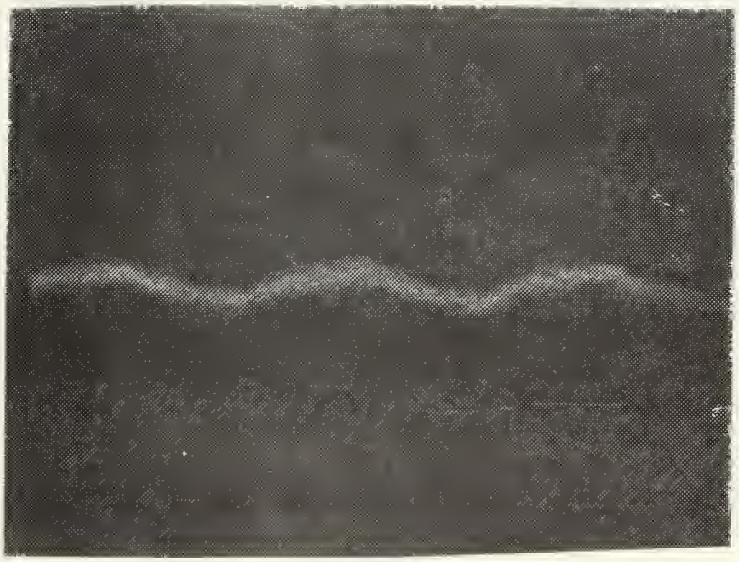
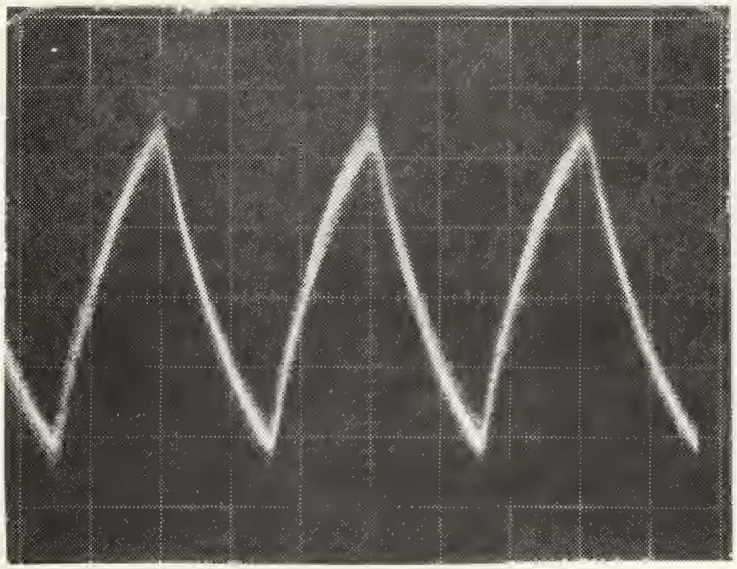


Figure 9

Sample 76D Before (above) and After Irradiation. Dose 6×10^7 Rads.



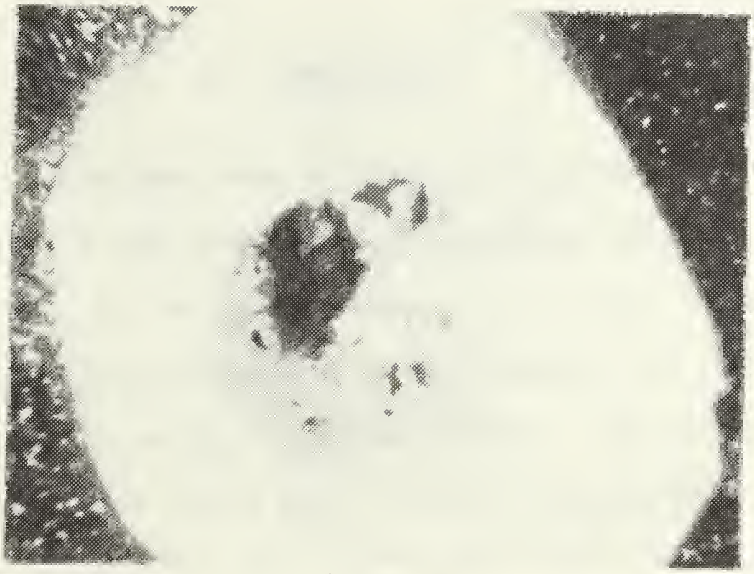
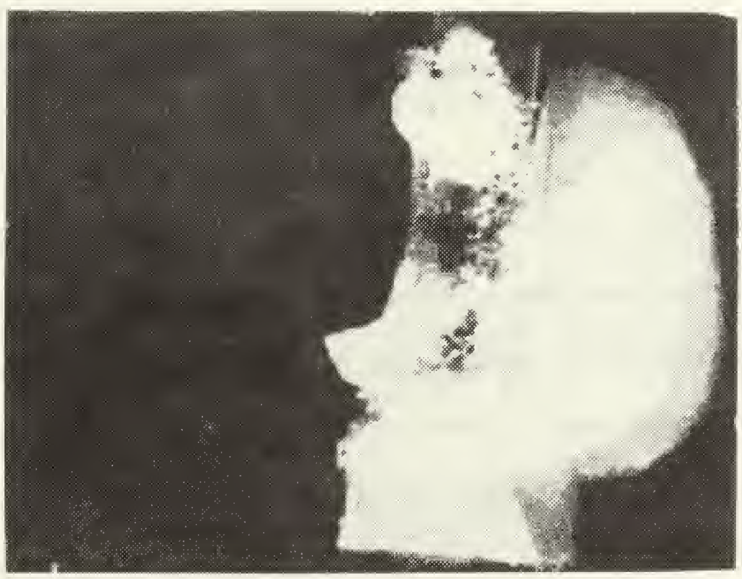


Figure 10

Plastic Cover and Sample 65C After
Irradiation Dose ~ 10^9 Rads.



VI. CONCLUSIONS

A total accumulated dose of 10^8 Rads or greater on this particular type SQUID has a high probability of rendering the device inoperative. Because of the limited number of samples available, and nine of the twelve samples being irradiated at approximately the same dose rate (10^5 Rads/sec) no really conclusive statement with respect to the effect of dose rate can be made. Table II appears to indicate that for a total accumulated dose of 10^6 Rads or less, and dose rates of 10^4 Rads/sec or less there is negligible permanent effect on the gross electrical response of the device, i.e., it will still superconduct and produce a signal of approximately the same amplitude as before irradiation. However, the same cannot be said of the circuit parameters necessary to produce the signal.

It would be difficult to relate the effects of radiation damage on the devices to the circuit parameters in any meaningful manner with the limited amount of data taken in this study, particularly in the total accumulated dose range of 10^7 Rads, until there is a better understanding of how the devices operate from first principles and the devices can be manufactured in a more controlled and reproducible manner. The bridge of these devices is in most respects exactly analagous to a point contact Josephson junction, in that if there is no contact (no bridge) no Josephson current will flow. As contact is made and the pressure is increased on the point (cross-sectional area of bridge increases) the amount of Josephson current will increase up to some maximum value. If the pressure is further increased (cross-sectional area of the bridge is further increased) the Josephson current will decrease and finally cease flowing.

In the devices studied here it is known that the maximum supercurrent that can flow is critically dependent on the cross-sectional area of the bridge. The maximum amplitude of the detected signal is in turn related to this maximum value of supercurrent. From the discussion in section I describing the process by which these devices are manufactured, it can be seen that this procedure allows for considerable variance between samples in the cross-section area of this critical part of the film.

This variance of the cross-sectional area of the bridge between devices suggests one possible explanation of the seemingly inconsistent results from one sample to the next for the same accumulated total dose. If it is assumed that a plot of the maximum supercurrent (plotted as the ordinate) versus the cross-sectional area of the bridge (plotted as the abscissa) would resemble to some degree one half period of a sine curve, then for a particular device that had a cross-sectional area before irradiation corresponding to a value greater than $\pi/2$ the critical supercurrent would be less than its maximum possible value. Irradiation then could introduce defects that would effectively decrease the effective cross-sectional area of the bridge to say a value corresponding to $\pi/2$ where the maximum supercurrent would flow and consequently one would see and increased amplitude in the detected signal. This would correspond to the case of sample 76D in Table II where the signal increased by a factor of eight after irradiation. On the other hand if the cross-sectional area of the bridge was such that the supercurrent was already near its maximum (corresponding to a value of $\pi/2$ on a sine curve) before irradiation then radiation defects introduced in the bridge would effectively decrease the effective cross-sectional

area of the bridge but now the supercurrent would also decrease, and consequently the detected signal. This would correspond to the case of sample 71C in Table II where the detected signal decreased after irradiation.

The major contribution of this study is that it could be used as a guide to determine at what dose and dose rate one might expect to observe significant radiation damage effects in future studies on these devices. There were none available in the literature when this study was initiated.

There are some implications about the use of these devices which may be made as a result of this study. For instance one suggested use of this device is as a space magnemometer to study the earth's magnetic field and variations in it due to solar flares and other physical phenomena, and the magnetic field of other planets as well. In some regions of space it is known that there are rather large radiation fields, for instance, the Van Allen radiation belt around the earth. If the parameters characterizing these radiation fields were known this study could be used as a guide in determining the survivability of such a space magnemometer in these environments.

The use of these devices in military hardware applications necessarily makes its response under the influence of fission and fusion weapon radiation environments of interest. If for instance, an order of magnitude calculation for the total dose deposited by the neutron flux of a low altitude ten kiloton fission weapon is performed, it is found that the device would have to be as close as two kilometers to ground zero to accumulate a dose of ~ 10^8 Rads (failure dose). This is assuming the device is neither shielded nor radiation hardened.

Since in order to operate these devices of necessity would have to be in a liquid helium environment inside a cryostat which in turn would be enclosed in some type container, the implication is that the sensor would be fairly radiation damage resistant when compared to the electronic components that must be used in conjunction with it. It is evident that the same would be true for the space magnomometer application.

APPENDIX A

A vibrating reed electrometer was used to measure the voltage across a capacitor charged by the electrons collected in a Faraday cup. The number of electrons collected by the cup (assumed to be 100 percent due to the dimensions of the cup as compared to the dimensions of the beam) can be computed from the voltage on the capacitor as follows:

$$Q = CV$$

$$Ne = CV$$

$$N = CV/e$$

N = Number of electrons collected

C = Capacitance

V = Voltage

e = Electronic charge.

The energy loss of the incident electrons is designated as α and is given by $\alpha = (1/\rho)(dE/dx)$ in Mev-cm^2/gm

ρ = density of the material

dE/dx = energy loss due to ionizations.

Values of α are tabulated in Ref. 10. From past experience and flux measurements on the Naval Postgraduate accelerator it is known that the fluence in units of e-/cm^2 is given approximately by

$$\phi = 4N$$

The total accumulated dose is therefore

$$D = (\alpha)\ (\phi)\ \text{Mev/gm}$$

$$1\ \text{Mev} = 1.6 \times 10^{-6}\ \text{ergs}$$

$$1\ \text{Rad} = 100\ \text{ergs/gm}$$

Therefore the total accumulated dose in Rads is given by

$$D = (1.6 \times 10^{-8})\ (\alpha)(\phi)\ \text{Rads}$$

Knowing that the time (t) for a given size capacitor to accumulate a charge (q) which is proportional to the voltage accumulated, the average dose rate can be calculated as

$$\frac{D}{t} = \frac{(1.6 \times 10^{-8})\ (\alpha)(\phi)}{t}\ \frac{\text{Rads}}{\text{sec}}$$

The time (t) for a given size capacitor to accumulate a voltage V is timed electronically at the NPS accelerator.

Various methods of dosimetry have been used to verify this method of calculation. It has been found that the measurements using this method are accurate to within a factor of two.

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

A Study of Permanent Electron Beam Radiation Effects on Thin Film Single Junction Quantum Interferometer Devices

4. DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis, June 1972

5. AUTHOR(S) (First name, middle initial, last name)

Richard G. T. Welsh

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1972	39	10

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Postgraduate School Monterey, California 93940

13. ABSTRACT

Mercereau-Nisenoff, single junction, superconducting, quantum interferometer devices were irradiated at room temperature with 60 Mev electrons.

After irradiation these devices showed no optically observable gross physical defects. There were, however four levels of electrical response to radiation damage dependent on the total accumulated dose as follows:

1. device would superconduct and the detected radio frequency signal amplitude remained essentially unchanged at a dose level of ~ 10^5 Rads,
2. device would superconduct but the detected radio frequency signal amplitude changed markedly at a dose level of ~ 10^7 Rads,
3. device would superconduct, but no detected radio frequency signal was observable also at a dose level of ~ 10^7 Rads,
4. device would no longer superconduct at a dose level of ~ 10^8 Rads.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

Security Classification

A-31405

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JID						
gnemometer						
diation Effects						
sephson Junction						
near Accelerator						
ectron Irradiation						

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c.1 A study of permanent electron beam radiation effects on thin film single junction quantum interferometer devices.